Displaced Vertices from Folded Supersymmetry

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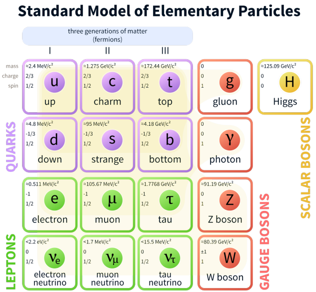
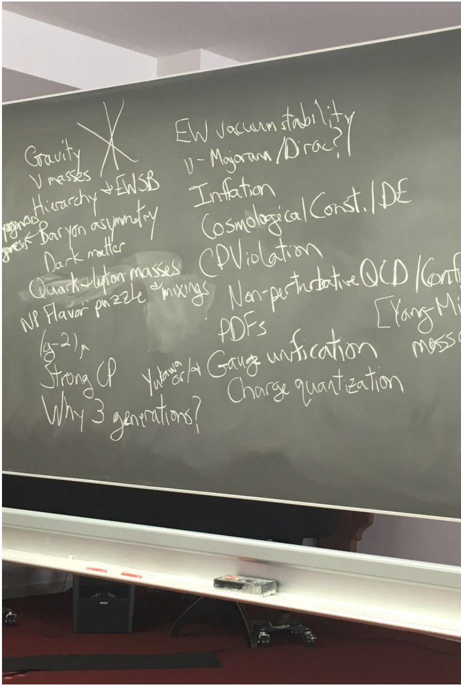
The Standard Model of Particle Physics

- Electroweak Interactions
  - $SU(2)_L \times U(1)_Y \to U(1)_{EM}$
  - Higgs Mechanism
- Strong Interactions $SU(3)_C$



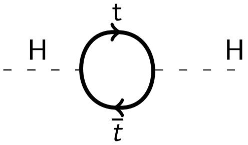
Unanswered questions

- Dark Matter
- Cosmological constant
- Gravity
- Neutrino masses
- Hierarchy problem of masses
- Hierarchy problem of scales
- ...



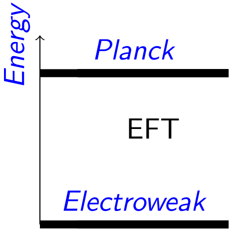
The Hierarchy Problem

- $m_H = 125 GeV \to \lambda \simeq 0.13$
- m_H is not protected by a symmetry
- Radiative corrections to Higgs boson mass are quadratic on Λ_{top}

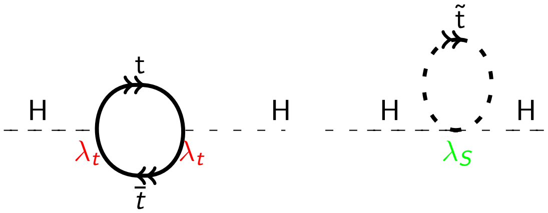


$$\delta m_H^2 = -N_C \frac{\lambda_t^2}{16\pi^2}(2\Lambda_{UV}^2) + \dots$$

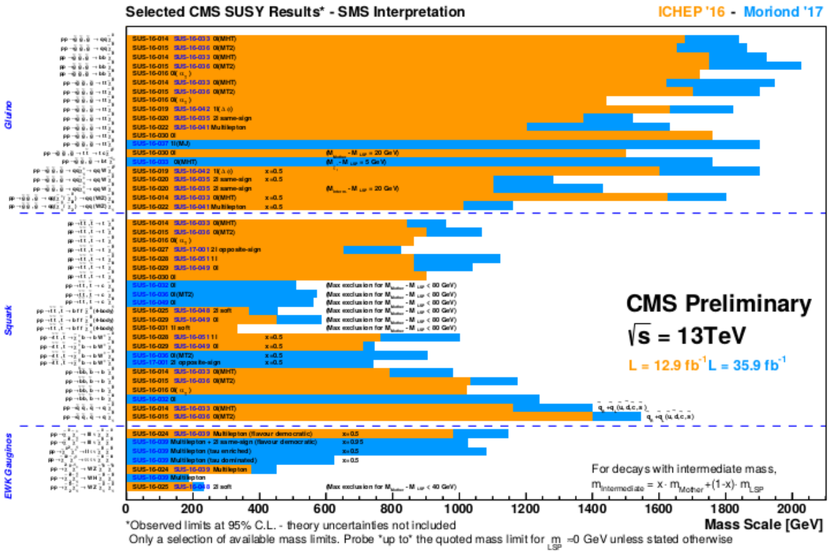
- Fine Tuning
- New physics



SUSY and Hierarchy Problem



$$\delta m_H^2 = -N_C \frac{\lambda_t^2}{16\pi^2}(2\Lambda_{UV}^2) + \dots \qquad \delta m_H^2 = +N_C \frac{\lambda_S}{16\pi^2}\Lambda_{UV}^2 + \dots$$


Selected CMS SUSY Results* - SMS Interpretation
ICHEP '16 - Moriond '17
Gluino
Squark
EWK Gauginos
CMS Preliminary
√s = 13TeV
L = 12.9 fb⁻¹ L = 35.9 fb⁻¹
For decays with intermediate mass,
m_intermediate = x· m_Mother +(1-x)· m_LSP
0 200 400 600 800 1000 1200 1400 1600 1800 2000
Mass Scale [GeV]
*Observed limits at 95% C.L. - theory uncertainties not included
Only a selection of available mass limits. Probe *up to* the quoted mass limit for m_LSP =0 GeV unless stated otherwise

- SUSY scale cannot be too big
- Radiative corrections to m_H depends on the stop mass

$$\delta m_H^2 = N_C \frac{m_{\tilde{t}}^2}{16\pi^2} \log\left(\frac{\Lambda_{UV}^2}{m_{\tilde{t}}^2}\right)$$

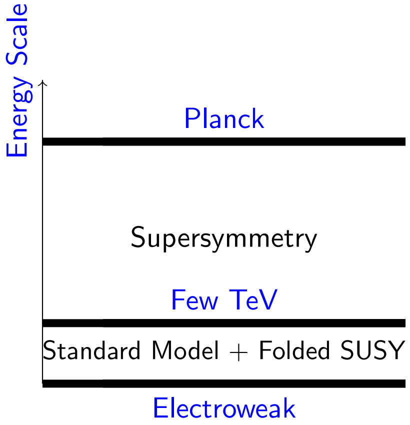
Neutral Natural models

- Colorless Top Partners;
- Extensions to the Color Group: $[SU(3)]^2$.

- Twin Higgs (Chacko, Goh Harnik hep-ph/0506256);
- Quirky Little Higgs (Cai, Cheng, Terning arXiv:0812.0843);
- Folded SUSY (Burdman, Chacko, Goh, Harnik, hep-ph/069152).

Folded SUSY (Burdman, Chacko, Goh, Harnik, 2006)

- Extension of Color Group
- $SU(3)_C \times SU(3)_{hidden}$
- UV completed with SUSY model
- SUSY broken by the Scherk Schwarz mechanism



Toy Model: Bifold Protection

- Global U(N) with a singlet S

$$W = \lambda S \bar{Q}_i Q_i, \quad i = 1, 2, \ldots N$$

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M_S quadratically divergent

- Supersymmetrize
- Double the number of quarks, U(2N)

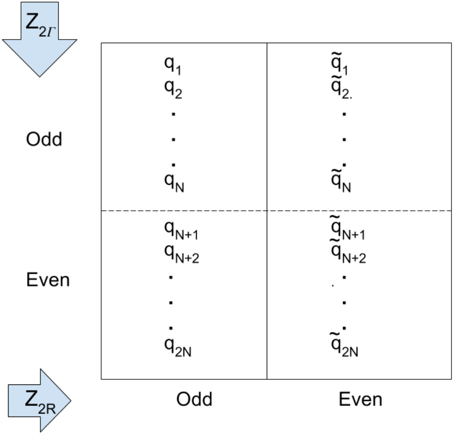
- Invariant under Z_{2R}

$$\begin{aligned} |boson\rangle &\to |boson\rangle, \\ |fermion\rangle &\to -|fermion\rangle \end{aligned}$$

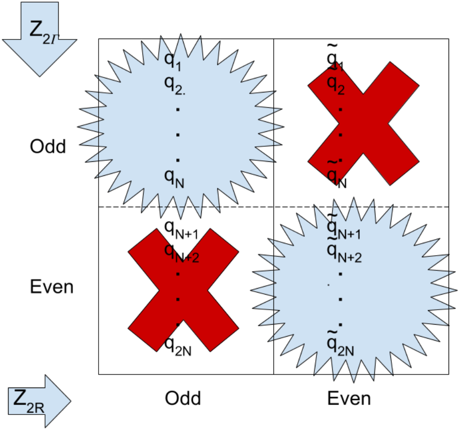
- and $Z_{2\Gamma}$

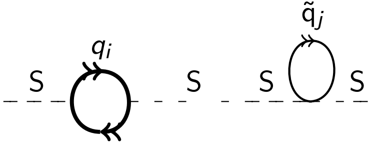
$$\Gamma = \begin{bmatrix} +1 & & & & & \\ & \ddots & & & & \\ & & +1 & & & \\ & & & -1 & & \\ & & & & \ddots & \\ & & & & & -1 \end{bmatrix}, \qquad \begin{aligned} S &\to S \\ Q_i &\to -\Gamma Q_i \\ \bar{Q}_i &\to -\Gamma^* \bar{Q}_i \end{aligned}$$

Accidental SUSY



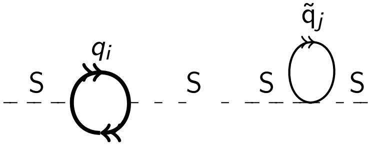
Orbifolding → Project out odd states under $Z_{2R} \times Z_{2\Gamma}$





$i = 1 \ldots N$,
$j = N + 1 \ldots 2N$

- Singlet is protected at 1 loop
- At 2 loop Singlet is quadratically divergent



$i = 1 \dots N,$
$j = N + 1 \dots 2N$

- Singlet is protected at 1 loop
- At 2 loop Singlet is quadratically divergent
- Squarks masses are not protected!

$$\delta m^2_{\tilde{q}} = -\frac{g^2}{16\pi^2}\Lambda^2 + \dots$$

Folded SUSY

- Extended Color Group $SU(3)_C \times SU(3)_{hidden} \times Z_2$
- Accidental SUSY (quarks and colorless f-squarks)
- m_H protected against radiative corrections

$$\mathcal{L}_Y = (\lambda_t h_u q_A u_A + h.c.) + \lambda_t^2 |\tilde{\mathrm{q}}_B h_u|^2 + \lambda_t^2 |\tilde{\mathrm{u}}_B h_u|^2.$$

The Scherk Schwarz Mechanism

- UV completion
- SUSY in 5D with one CED
- Broken by boundary conditions
- 4D daughter theory with Accidental SUSY

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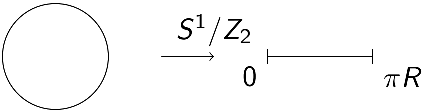


Figure: Orbifolding mechanism

$SU(6) \times SU(2) \rightarrow SU(3)_A \times SU(3)_B \times SU(2) \times U(1)$

Quarks

$$\hat{Q}_{iA}(3, 1, 2, 1/6)$$
$$\hat{U}_{iA}(\bar{3}, 1, 1, -2/3)$$
$$\hat{D}_{iA}(\bar{3}, 1, 1, 1/3)$$

Squarks

$$\hat{Q}_{iB}(1, 3, 2, 1/6)$$
$$\hat{U}_{iB}(1, \bar{3}, 1, -2/3)$$
$$\hat{D}_{iB}(1, \bar{3}, 1, 1/3)$$

Yukawa Interactions

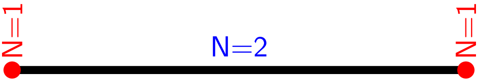
$$W = \delta(y)\lambda_t[Q_{3A}H_U U_{3A} + Q_{3B}H_U U_{3B}],$$

After SUSY Breaking

$$\mathcal{L}_Y = (\lambda_t h_u q_A u_A + h.c.) + \lambda_t^2|\tilde{\mathrm{q}}_B h_u|^2 + \lambda_t^2|\tilde{\mathrm{u}}_B h_u|^2.$$

F-Squark masses at 1 loop

(A. Delgado, A. Pomarol, M Quiros, hep-ph/9812489)



$$m_Q^2 = K\frac{1}{4\pi^4}\left(\frac{4}{3}g_3^2 + \frac{3}{4}g_2^2 + \frac{1}{36}g_1^2\right)\frac{1}{R^2}$$

$$m_U^2 = K\frac{1}{4\pi^4}\left(\frac{4}{3}g_3^2 + \frac{4}{9}g_1^2\right)\frac{1}{R^2}$$

$$m_D^2 = K\frac{1}{4\pi^4}\left(\frac{4}{3}g_3^2 + \frac{1}{9}g_1^2\right)\frac{1}{R^2}$$

For 3^{rd} Generation f-squark:

$$m_{3Q}^2 = K\frac{\lambda^2}{8\pi^4}\frac{1}{R^2},$$

$$m_{3U}^2 = K\frac{\lambda^2}{4\pi^4}\frac{1}{R^2}$$

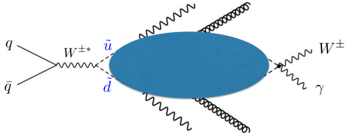
F-squarks production at the LHC

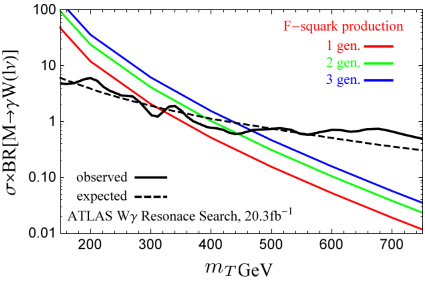
(Burdman, Chacko, Goh, Harnik, Krenke, 0805.4667)

- Charged Currents
  - $W\gamma$ resonance
- Neutral Currents
  - Colorless glueball $\rightarrow$ Displaced vertices

$W\gamma$ bounds on LHC Run I

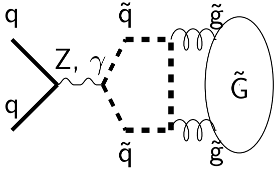
(Burdman, Chacko, Harnik, Lima, 2014)

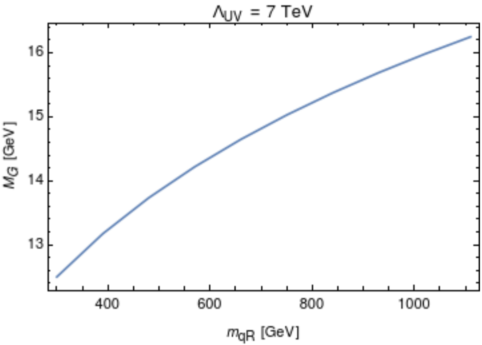




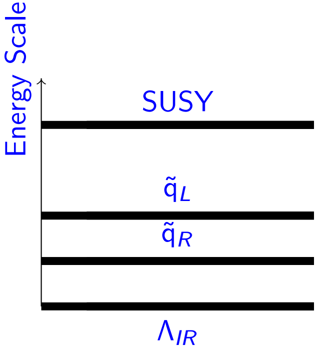
Signals (Burdman, Lichtenstein, In Preparation)

- Decay of f-squarks into Glueballs is prompt
- Decay of Glueballs into SM through Higgs (Craig, Katz, Strassler, Sundrum 1501.05310)




Λ_{UV} = 7 TeV
16
15
14
13
M_G [GeV]
400
600
800
1000
m_{qR} [GeV]

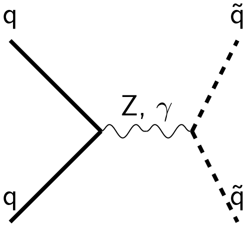
Folded Strong Coupling



$M_{\tilde{G}} \sim 7\Lambda_{IR}$
(Georgi, Nakay, arxiv:1606.05865)

$$\beta_F = -g_F^3 \frac{1}{(4\pi)^2}\left(11 - \frac{N_S}{6}\right)$$

Production of f-squarks



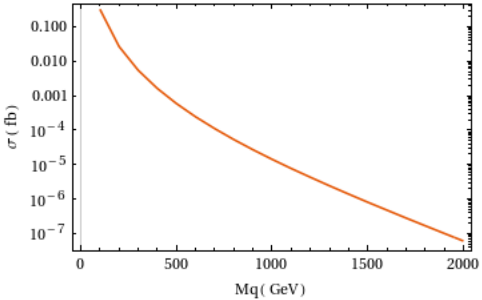
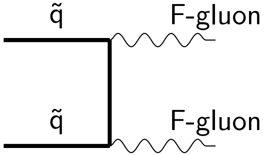


Figure: Cross Section at 13 TeV
p p $\rightarrow$ (γ or Z) $\rightarrow$ $\tilde{q}$ $\tilde{q}$.

Glueball production



$$\frac{d\sigma}{dE_h}(AB \to hX) = \sum_k \int \frac{d\sigma}{dE_k}(AB \to kX) D_k^h \left(\frac{E_h}{E_k}\right) \frac{dE_k}{E_k}.$$

Fragmentation Function

$$D(z) = N(1-z)^{\beta}$$
$$z \equiv \frac{E_h}{E_k}.$$

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$$\int z \times D(z) dz = 1$$

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$$< N >= \int D(z) dz$$

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DGLAP evolution

$$\frac{dD_k^h(z,\mu)}{d\log\mu} = \frac{\alpha(\mu)}{2\pi}\int_0^1 \frac{dw}{w} D_k^h\left(\frac{z}{w},\mu\right) {\color{red}P(w)}.$$

Gluon Splitting Function

$$P_{gg}(z) = \alpha P^0 + \alpha^2 P^1 + \alpha^3 P^2 + \dots$$

$$P^0_{gg}(z) = 6\left(\frac{1-z}{z} + \frac{z}{[1-z]_+} + z(1-z) + \frac{11}{12}\delta(1-z)\right).$$

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It does not work for **small z** values $\alpha_s Log^2(1/z) \approx 1$

Low z approximation

$$D(z) \propto \frac{1}{z} exp \left[-\frac{1}{2\sigma^2}(\xi - \xi_p)^2 \right]$$

$$\xi \equiv ln(1/z)$$

$$\xi_p = \frac{1}{4b\alpha_F}$$

$$\sigma^2 = \frac{1}{24b}\sqrt{\frac{2\pi}{C_A \alpha_F^3}}$$

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$$< N > \propto exp\left[\frac{1}{b}\sqrt{\frac{6}{\pi\alpha_F}} + \left(\frac{1}{4}\right) ln\alpha_F\right]$$

Modeling the Fragmentation Function

$$D(z) = N(1-z)^{\beta}$$

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Strategy 1

- Start at an energy scale μ_0.
- Match low and high z behavior at some value z_M
- Choose a value of β. E.g. $\beta = 1$
- Impose normalization (energy conservation). This fixes $D(z, \mu_0)$ (and $< n > (\mu_0)$)
- Evolve to other energies using DGLAP

Modeling the Fragmentation Function

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Strategy 2

Modeling the Fragmentation Function

$$D(z) = N(1-z)^{\beta}$$

Strategy 2

- Matching low and high z behaviour

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- Fragmentation Function is mostly dominated by low z behaviour

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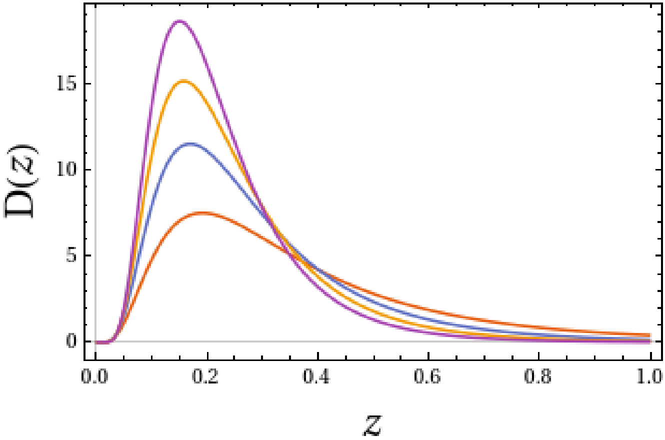
$$D(z) \propto \frac{1}{z} exp\left[-\frac{1}{2\sigma^2}(\xi - \xi_p)^2\right]$$

$$< N > \propto exp\left[\frac{1}{b}\sqrt{\frac{6}{\pi\alpha_F}} + \left(\frac{1}{4} + \frac{5n_f}{54\pi b}\right) ln\alpha_F\right]$$



$m_{\tilde{q}_R}$ [GeV] 900 700 500 300
($z_M = 0.1$, $M_{\tilde{G}} = 15$ GeV, $\Lambda = 7$ TeV)

Glueball Lifetime

0^{++} glueballs decay back to SM through HDOs
(N. Craig, A. Katz, M. Strassler, R. Sundrum 1501.05310)

$$O \sim H^\dagger H \tilde{\mathrm{G}}_{\mu\nu} \tilde{\mathrm{G}}^{\mu\nu},$$

Decay width (D. Curtin, C. Verhaaren 1506.06141)

$$\Gamma(\tilde{\mathrm{G}} \to SM) \approx \frac{1}{144\pi^4} \frac{c^4}{m^4_{\tilde{\mathrm{q}}_R}} \frac{v^3}{(m_h^2 - M^2_{\tilde{\mathrm{G}}})^2} (4\pi\alpha_F F_G)^2 \Gamma(h \to SM)(M^2_{\tilde{\mathrm{G}}})$$

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Glueball decay constant (from lattice)

$$4\pi\alpha_F F_G \approx 2.3 M_{\tilde{\mathrm{G}}}^3$$

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$$4\pi\alpha_F F_G \approx 2.3 M_{\tilde{G}}^3$$

$$\Gamma(\tilde{G} \to SM) \approx \frac{M_{\tilde{G}}^7}{m_{\tilde{q}_R}^4}$$

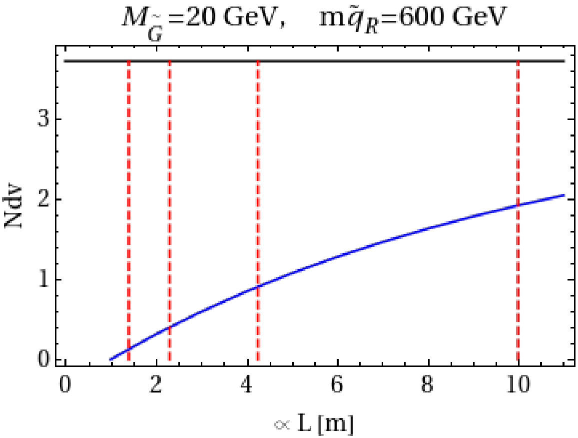
Distribution of Displaced Vertices

$$N_{DV} = \int dz D(z,s)(1 - e^{-\frac{L}{L_G}}) \tag{0.1}$$

$$L_G = c\tau_G \frac{x}{x_{min}} \tag{0.2}$$

$$c\tau_G \approx \frac{m^4_{\tilde{q}_R}}{M^7_{\tilde{G}}} \tag{0.3}$$

ATLAS detector layers



Tracker ECal HCal Muon

Conclusions

- Neutral Natural models as a solution to the little hierarchy problem
- Folded SUSY
- Production of F-squarks at the LHC
- F-Glueballs
- Displaced vertices distribution